Design and Implementation of Channel Estimation and Equalization of Indoor Positioning System Based on UWB

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Abstract: Precise indoor positioning is becoming increasingly important in commercial, military and public service applications for tracking people and asset. Ultra Wide Band (UWB) can provide high accuracy position with strong anti-jamming and low power consumption. For highly dispersive channels, an orthogonal frequency-division multiplexing (OFDM) RX is more efficient at capturing multipath energy than an equivalent single-carrier system using the same total bandwidth. OFDM systems possess additional desirable properties, such as high spectral efficiency, inherent resilience to narrow-band RF interference, and spectral flexibility, which is important because the regulatory rules for UWB devices have not been finalized throughout the entire world, so MB-OFDM modulation is selected in indoor positioning system based on UWB.

Channel estimation and equalization are key technologies in the indoor positioning system. Some systems based on MB-OFDM modulation adopt continuous modulation rather than differential modulation in considering of saving transmission power and providing relatively high data rates. Hence, coherent detection is required in receiver, which needs an estimation and compensation of the channel impulse response (CIR) before the demodulation. Channel estimation can be avoided by using differential modulation, but there is a 3dB loss in signal-to-noise ratio (SNR) approximately. So channel estimation and equalization are very important and can not be ignored.

Analysis and implementation of indoor positioning systems based on UWB require an accurate channel model to determine that can be achieved, to design efficient modulation and coding schemes, and to develop associated signal-processing algorithms and effective method of hardware implementation. The structure of indoor positioning system based on UWB is introduced and some system parameters and modulation are determined in this paper. After description the structure of receiver and transmitter of system, a detailed analysis of UWB indoor channel characteristics is given and some algorithms of channel estimation and equalization are discussed in this paper. Some channel estimation techniques based on preamble training sequences and pilot sub-carriers are researched in depth. Further more, the linear estimations of least square (LS) and minimum mean square error (MMSE) are analyzed and compared under different UWB channel conditions and then suitable algorithm for this system is selected. Based on this selection, a scheme for FPGA implementation is proposed, and then some most significant modules for channel estimation and equalization has validated with Xilinx Virtex IV FPGA. It has been shown by some modelsim simulations that this channel estimation and equalization approach has some merits, such as simple implementation and less consumption of resource. It can meet the requirement of system design and some good performances can be achieved.

1. Introduction

Geographic location information can be retrieved by various infrastructures and
technologies [1]. Satellite navigation system is effective and accurate outdoors, but it works very poorly, if at all, indoors and in urban canyon environments. Cellular networks can be used to provide location services, where the mobile stations are located by measuring the signals traveling to and from a set of fixed cellular base stations. However, owing to the low power of each transmitter and narrow bandwidth, position systems based on cellular networks can only achieve very limited accuracy with location error often larger than few hundred meters [2, 3]. Position location system based on UWB (Ultra wide band, UWB) is more accurate within room [4] which is provided by good time resolution, high data rate, low system power cost, and high multi-Path immunity of UWB.

In recent years, UWB communication systems have received significant attention from both the industry and the academia. In February 2002, the Federal Communications Commission (FCC) allocated 7,500 MHz of spectrum (from 3.1 GHz to 10.6 GHz) for use by UWB devices [5, 6]. This ruling has helped to create new standardization efforts, like IEEE 802.15.3a [7], that focus on developing high speed wireless communication systems for personal area network.

A multi-band orthogonal frequency division multiplexing (MB-OFDM) ultra wideband (UWB) system is being considered for the physical layer of the new IEEE wireless personal area network (WPAN) standard, IEEE 802.15.3a [7]. The standard aims at the high data transmission rates of 110 Mb/s over 10 meters, 220 Mb/s over 4 meters and 480Mb/s over 1 meter [8].

Channel estimation and equalization are key technologies in the indoor positioning system based on MB-OFDM. Channel estimation can be avoided by using differential modulation, but there is a 3dB loss in signal-to-noise ratio (SNR) approximately. So channel estimation and equalization are very important and can not be ignored.

Field programmable gate array (FPGA) technology is not only a key technology in digital system, but also plays an important role in application specific integrated circuit (ASIC) design field because of its design flexibility, and higher integration [9]. The technical line for the implementation of channel estimation and equalization with Xilinx Virtex II series FPGA is introduced in this paper. It has been proved by the simulation results that the design of channel estimation and equalization based on FPGA has good characteristics such as simple structure, easy implementation, high reliability and so on.

The paper is organized as follows. Section 2 provides a description of the structure of indoor positioning system based on UWB. The design of channel estimation and equalization of system discussed in section 3. Section 4 provides performance results of channel estimation and equalization based on Xilinx Virtex II FPGA simulations and section 5 concludes this paper.

2. The structure of indoor positioning system based on UWB

Fig.1 shows the structure of indoor positioning system based on UWB which is comprised of four fixed transmitters (TX) and one mobile receiver(RX). The receiver receives some signal which is transmitted from four fixed transmitters and then gives positioning solutions by acquisition and Tracking within receiver.
The transceiver’s structure is shown as Fig. 2.

At the transmitter, after scrambling, encoding/puncturing and bit interleaving, the binary serial data shall be mapped into constellation points according to the Gray-coding. Here, continuous modulation such as quadrature phase-shift keying (QPSK) is recommended. Then the stream of complex symbols is mapped into coefficients of IFFT [10].

For low complexity solution, an FFT size of 256 points is too big. However, a FFT size smaller than 64 points will increase the overhead due to zero-padded (ZP) suffix. An optimal FFT size for UWB system is 128, which provides a balance between performance and complexity [6].

Out of the 128 sub-carriers in each OFDM symbol, 100 are allocated to data and 12 are dedicated to pilots uniformly inserted into the OFDM symbol. The 10 guard subcarriers, with five on either edge of the OFDM symbol occupied band, are created by copying the five outermost data subcarriers. The rest six IFFT input are set to zero.

After performing the IFFT, a ZP suffix of length 37 is appended to eliminate ISI and capture sufficient multi-path energy to minimize the impact of inter-carrier interference (ICI).

At the receiver, the signals from the antenna first pass through the analog front-end to obtain the in-phase and quadrature digital signals. These signals are then demodulated by the FFT module using either sequential channel processing or parallel channel processing methods. The data is then processed by the diversity combining block to enhance the performance and robustness of the system. The QPSK de-mapper translates the symbol back into bits before being re-permuted by the de-interleavers. The de-inner-interleaver and de-inter-interleaver blocks reorder the data back into the original order. Finally, the Viterbi decoder estimates the corresponding transmitted data.

3. Channel estimation and Equalization

3.1 Channel model

The time of arrival of multi-path components is not continuous and represents the characteristic of “clustering” [11] [12]. Here, a lognormal distribution rather than a Rayleigh distribution is recommended to describing the received envelope and multi-path gain magnitude. The Saleh-Valenzuela (S-V) multi-path models unique in modeling arrivals in clusters, as well as rays within a cluster. With minor modifications to the S-V model, the multi-path UWB channel impulse response indiscrète time form can be expressed as

\[ h_i(t) = X_i \sum_{l=0}^{L_i} \sum_{k=0}^{K} \alpha_{k,l}^i \delta(t - T_i^l - \tau_{k,l}^i) \] (1)

Where i refers to the impulse response realization, l refers to the cluster, and k refers to the ray within the cluster. \( \alpha_{k,l}^i \) is the multi-path gain coefficient conforming to the lognormal distribution; \( T_i^l \) is the delay of the lth cluster; \( \tau_{k,l}^i \) is the delay of the kth ray relative to \( T_i^l \); \( X_i \) represents the lognormal shadowing. The ability of UWB receiver to resolve multi-path is significantly increased for large bandwidth.

Fig. 3 illustrated channel impulse respond of four kinds of UWB channel models (CM1-CM4).
CM1-CM4 stand for channel environment is shown as Tab.1.

Fig.3 Channel impulse respond for CM1-CM4

Fig.1 CM1-CM4 stand for UWB channel environments

<table>
<thead>
<tr>
<th>Channel model</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>LOS (0-4m)</td>
<td>NLOS (0-4m)</td>
<td>NLOS (4-10m)</td>
<td>Extreme NLOS</td>
</tr>
<tr>
<td>RMS delay (ns)</td>
<td>5.28</td>
<td>8.03</td>
<td>14.28</td>
<td>25</td>
</tr>
</tbody>
</table>

As shown in Fig.4, time delay because of channel cannot be ignored.

3.2 Channel estimation and equalization

Channel estimation and equalization is a core part of receiver. Channel estimation and equalization based on preamble is one of the most common methods because of low complexity of implementation, so channel estimation and equalization based on preamble is selected in this systems.

The transmitted samples can be represented by

\[ X(k) = X(ml + l) = \begin{cases} X(m) & l = 0 \\ X_p(m) & l = 1, 2, ..., L - 1 \end{cases} \]  (2)

Where \( L \) is the interval between pilot and \( X_p(m) \) is the \( m^{th} \) preamble symbol.

Preamble can be expressed as follow

\[ X_p = \text{diag}\{X_p(0)X_p(1)....X_p(N_p - 1)\}^T \]  (3)

The frequency response on the location of pilot is

\[ H_p = \{H_p(0)H_p(1)....H_p(N_p - 1)\}^T \]  (4)

So the received pilot sequence is

\[ Y_p = \{Y_p(0)Y_p(1)....Y_p(N_p - 1)\}^T \]  (5)

\[ Y_p = X_pH_p + N_p \]  (6)

Where \( N_p \) is Additive White Gaussian Noise (AWGN) with zero-mean and variance 0 \( N \) at the location of preamble. The estimation at the preamble sub-carriers can be also based on the linear estimations of least square (LS) or minimum mean square error (MMSE). Fig.4 shows the performance compare with MMSE and LS algorithm. The MMSE estimation has better performance than LS estimation for exploiting the prior information on channel. However the computational complexity is higher consequently. So LS is widely used in practical system and is selected in this system.

Fig.4. performance compare with MMSE and LS algorithm

The expression of frequency domain LS estimation can be expressed as follow.

\[ H_{p,LS} = X_p^{-1}Y_p = H_p + N_p / X_p \]  (7)

The channel equalization is used as complement the effect of channel impulse respond. Zero forbidden (ZF) algorithm is usually used in OFDM system, so the results after channel
equalization based on ZF algorithm can be described as

\[ G_{ZF} = (H^H H)^{-1} H^H Y_p \] (8)

So channel estimation and equalization can be obtained.

4. Implementation of channel estimation and equalization

According to the results described above, the hardware implementation structure of channel estimation and equalization can be obtained. As shown in Fig.5, it is comprised of three parts: valid data extraction, channel estimation and equalization.

4.1 Valid data extraction

Each OFDM symbol consists of 37 zero suffixes and 128 data points. FFT for channel estimation, the zero suffix is not involved in operations, so in prior to channel estimation, need to remove the zero suffix, extract valid data. Effective use of RAM to achieve data extraction, design of a RAM of 165 × 10 to achieve, read 165 10-bit data, through the address selection output 128 10-bit effective data. The modelsim simulation of valid data extraction is shown in Fig.6. 1-165 simulation data stream is used, 128 data in front of this data stream has been extracted.

\[ X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi nk/N} \quad k=0,...,N-1 \]

Where \( N \) is transform size, \( j = \sqrt{-1} \). \( X(k) \) for IDFT is

\[ x(n) = \frac{1}{N} \sum_{k=0}^{N-1} e^{j2\pi nk/N} \quad n=0,1,...,N-1 \]

The realization of the system using FFT pipeline stream structure, IP Core: Fast Fourier Transform v3.1 which the Xilinx offers is used for the realization of FFT algorithm. The modelsim simulation of FFT is shown in Fig.7.

4.2 FFT

FFT is an effective calculation of discrete Fourier transform (DFT) algorithm. \( X(n) \) is DFT of data stream \( x(n), n=0,\ldots,N-1 \) can be defined as

![Fig.5. Implementation structure of channel estimation and equalization](image)

![Fig.6. The modelsim simulation of data extraction](image)

![Fig.7. The modelsim simulation of FFT](image)

![Fig.8. The synthesized RTL schematic of channel estimation and equalization](image)

![Fig.9. Occupancy resources of channel estimation and equalization](image)
the data which is obtained by Matlab. Fig. 10 gives the compared result.

![Fig. 10 FPGA and Matlab data comparison](image)

As shown in Fig. 10, the data which is obtained by FPGA simulation is consistent with the Matlab data. Contribute to effect of channel noise, there is a slight deviation between this two data streams.

5. Conclusion

The indoor positioning system based on MB-OFDM and the transceivers of this system have been introduced in this paper. UWB indoor channel models have been discussed and the algorithms of channel estimation and equalization have been studied in this paper. The implementation projects of channel estimation and equalization has been described. It has been proved by simulation results that the design and implementation projects is correct and reasonable.

6. References


